A NOVEL PHOTONIC CLOCK AND CARRIER RECOVERY DEVICE

X. Steve Yao, George Lutes, and Lute Maleki
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA

Abstract

As data communication rates climb toward ten Gb/s, clock recovery and synchronization become more difficult, if not impossible, using conventional electronic circuits. We present in this article experimental results of a high speed clock and carrier recovery using a novel device called the photonic oscillator that we recently developed in our laboratory. This device is capable of recovering clock signals up to 70 GHz. To recover the clock, the incoming data is injected into the photonic oscillator either through the optical injection port or the electrical injection port. The free running photonic oscillator is tuned to oscillate at a nominal frequency equal to the clock frequency of the incoming data. With the injection of the data, the photonic oscillator will be quickly locked to the to the clock frequency of the data stream while rejecting other frequency components associated with the data. Consequently, the output of the locked photonic oscillator is a continuous periodical wave synchronized with the incoming data or simply the recovered clock. We have demonstrated a clock to spur ratio of more than 60 dB of the recovered clock using this technique. Similar to the clock recovery, the photonic oscillator can be used to recover a high frequency carrier degraded by noise and an improvement of about 50 dB in signal-to-noise-ratio was demonstrated.

The photonic oscillator has both electrical and optical inputs and outputs and can be directly interfaced with a photonic system without signal conversion. In addition to clock and carrier recovery, the photonic oscillator can also be used for 1) stable high frequency clock signal generation, 2) frequency multiplication, 3)square wave and comb frequency generation, and 4) photonic phase locked loop.

INTRODUCTION

Clock recovery by optically injection-locking a microwave oscillator[1] or a pulsed laser with an incoming data stream have been demonstrated by many authors[2-6] with varied degrees of success. In this paper, we report a different clock/carrier recovery scheme based on injection locking a novel photonic oscillator[7] we will refer to as a Light Induced Microwave Oscillator (LIMO).[8, 9] This oscillator converts continuous light energy into a spectrally pure microwave signal and can operate up to 75 GHz with phase noise below -140 dBc/Hz at 10 kHz frequency offset. This scheme can recover a clock or carrier from both optical and electrical data signals. Equally important, the recovered clock/carrier is also in both the optical and electrical domains.

Report Documentation Page

Form Approved
OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
DEC 1995		**00-00-1995 to 00-00-1995**

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
A Novel Photonic Clock and Carrier Recovery Device	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **California Institute of Technology,Jet Propulsion Laboratory,Pasadena,CA,91109**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
27th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, San Diego, CA, 29 Nov - 1 Dec 1995

14. ABSTRACT
see report

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**Same as Report (SAR)**	**10**	

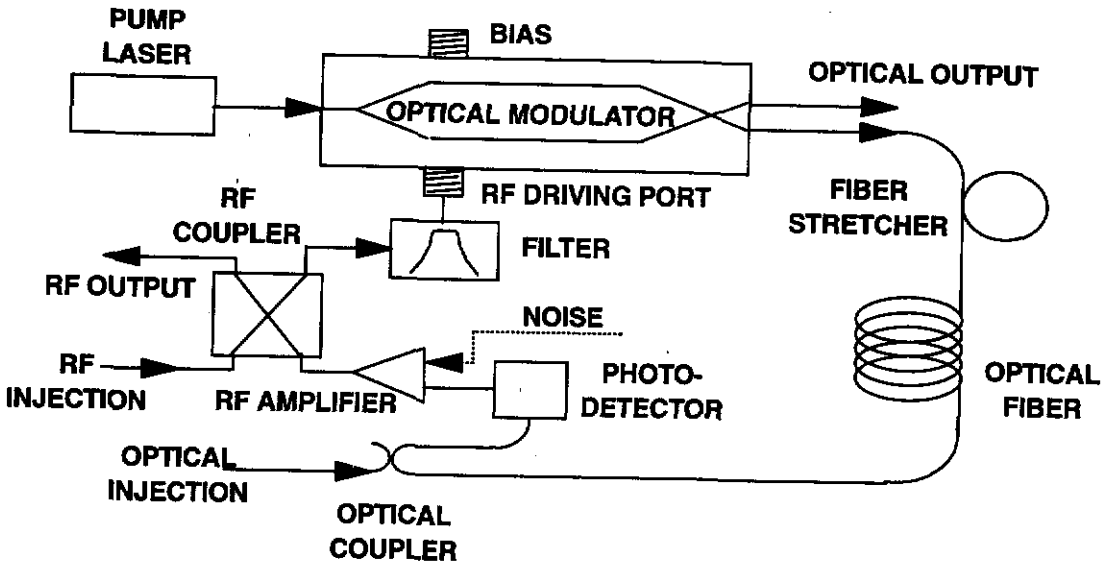


Fig. 1 Schematic of the LIMO.

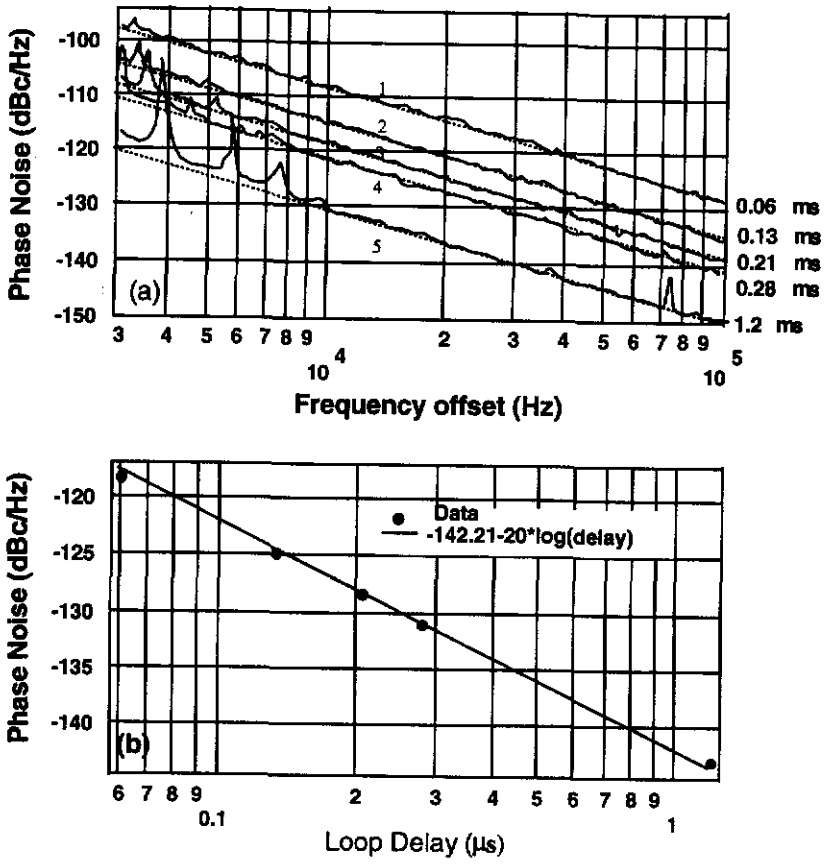


Fig. 2 The theoretical and measured phase noise of the LIMO as a function of the delay in the delay line.

This hybrid nature of the LIMO based device makes interfacing with a photonic transmission system simple.

The superior performance of the LIMO results from the use of electrooptic and photonic components which are generally characterized with high efficiency, high speed, low dispersion, and low loss at RF and microwave frequencies.

The LIMO takes advantage of the high equivalent Q of a long optical delay line to achieve highly stable narrow linewidth oscillation. Its spectral purity surpasses that of the best crystal oscillators particularly at high frequencies.

DESCRIPTION

Referring to Figure 1, light from a laser is applied to an E/O modulator, the output of which is launched into a long optical fiber and detected with a photodetector. The output of the photodetector is amplified and filtered then fed back to the electrical port of the modulator. This configuration supports self sustained oscillations, at a frequency determined by the delay in the optical fiber, modulator bias setting, and the bandpass characteristics of the filter. It also provides for both electrical and optical inputs and outputs. An analysis of the LIMO, which is beyond the scope of this paper, was given previously[8].

There are two important characteristics of the LIMO for frequency and timing applications. The phase noise is reduced by increasing the length of the delay line and the phase noise is independent of frequency. Figures 2(a and b) show the theoretical and measured phase noise of the LIMO as a function of the delay in the delay line and Figures 3(a and b) show the phase noise of the LIMO at different frequencies.

EXPERIMENT

The LIMO can recover a clock or carrier from both optical and electrical signals. Equally important, the recovered clock or carrier is also in both the optical and electrical domains. This hybrid nature of the LIMO based device makes interfacing with a photonic communication system simple.

In the case of clock recovery incoming data is injected into the LIMO either optically or electrically. The free running LIMO is tuned to oscillate at a nominal frequency close to the clock or carrier frequency of the incoming signal. With the injection of the incoming signal, the LIMO will quickly lock to its clock or carrier frequency while rejecting other frequency components (harmonics and subharmonics) associated with the signal.

Figure 4 shows the experimental setup used to demonstrate 100 MHz and 4.95 GHz clock recovery. Switches SW-1 and SW-2 are in the 'A' position for the 100 MHz clock recovery experiment and in position 'B' for the 4.95 GHz clock recovery experiment. In either experiment, using switch SW-3, we could choose to look at the LIMO output in the time domain with a Tektronix 2465B oscilloscope or in the frequency domain with an HP 8562 spectrum analyzer.

In the 100 MHz clock recovery experiment we used an HP 8080 Word Generator System to generate a stream of repetitive 64-bit words at 100 Mb/s and we tuned the LIMO to oscillate near 100 MHz. We injected the data into the bias port of the E/O modulator through a filter and a bias T. The 100 MHz filter with a 3 dB bandwidth of 10 MHz was used to reduce unwanted frequency components of the input data. We used the first bit of each word to trigger the oscilloscope's sweep so the whole word could be displayed. The HP 8080 system's data pattern can be selected to be either return-to-zero (RZ) or non-return-to-zero (NRZ) so both types of data were used in our experiments. Clock recovery is independent of the word chosen, as long as it is balanced. However, for an infinitely long NRZ random data stream, the clock frequency component is zero. In order to recover the clock from such a data stream a procedure to convert NRZ data format to RZ format is required.[10]

Figure 5 is the oscilloscope display of the experimental results in the time domain that demonstrated successful clock recovery from an NRZ data stream. Figure 5a shows the input data, while Figure 5b and Figure 5c show the recovered clock. In Figure 5c the time span was reduced 10 times to show the recovered clock in more detail. In all three figures, the upper trace is the first bit of the input data used to trigger the oscilloscope. The fact that the recovered clock can be clearly displayed on the oscilloscope when the first bit of data is used as the trigger indicates that the recovered clock is synchronized with the data.

When viewed in the frequency domain on the spectrum analyzer, the input data stream has some frequency components stronger than the clock frequency. After clock recovery the power of the recovered clock is more than 62 dB above the strongest frequency component of the data.

Note that the recovered clock level is almost independent of the input signal level, a feature that is desirable for clock recovery and is inherent in injection locked oscillators. Other proposed high speed clock recovery circuits use automatic gain control and limiting amplifiers to achieve constant amplitude.[11]

To extend our clock recovery experiment to higher data rates we simulated a stream of 4.95 Gb/s data by up converting a stream of 100 Mb/s RZ data using an RF mixer as shown in Fig. 4 with switches SW-1 and SW-2 in the 'B' position. The LIMO used in these experiments was constructed using an electrooptic modulator made by E-Tek Dynamics. We used a common reference signal from a hydrogen maser to synchronize the word generator and an HP 8672A synthesized signal generator. The frequency of the signal generator's output was chosen to be 4.85 GHz and was used to up convert the 100 Mb/s RZ data from the word generator to 4.95 GHz. The signal out of the mixer has a center band, an upper sideband and a lower sideband, which all contain the data information. We used a filter centered at 5 GHz with a bandwidth of 255 MHz to select only the upper sideband, which effectively simulated a stream of 4.95 Gb/s RZ data.

Figures 6a and 6b show the frequency spectrum of the data before and after clock recovery respectively. As expected, the clock frequency was strongly amplified by the LIMO while other frequency components remained unchanged, resulting in a recovered clock with a signal-to-spur ratio of about 60 dB.

Although in the demonstrations the data were injected into the electrical injection port, similar results are expected if the data are in the optical domain and are injected into the LIMO through the optical injection port, since the data in the optical domain will be automatically converted by the internal photodetector into the electrical domain before affecting the LIMO. We estimate that only a few microwatts of optical signal power is required to ensure a satisfactory clock recovery for many applications. Clock recovery via optical injection is important because it enables the clock of a high-speed data stream in a fiber-optic system to be directly recovered without first converting the data to electrical pulses.

Similar to clock recovery, a carrier buried in noise can also be recovered by the LIMO. In the experiment, we added noise to a clean 100 MHz test signal and adjusted the Signal-to-Noise-Ratio (SNR) until it was approximately 3 dB in a 100 kHz bandwidth. After carrier recovery, the SNR of the test signal was improved more than 50 dB. Figure 7 is the spectrum analyzer display of the signal before and after recovery. The frequency span of the spectrum analyzer was set to 10 MHz and its resolution bandwidth was set to 100 kHz.

CONCLUSION

We have demonstrated a novel photonic oscillator with an operation frequency up to 75 GHz, limited only by the speed of the E/O modulator used in the LIMO. It can be controlled and accessed both optically and electronically, making it attractive for easily interfacing with a complex fiber optic systems. We have demonstrated its use for clock or carrier recovery with very low phase noise. We have also shown that the LIMO has a number of other attractive properties including output power which is virtually independent of the input power of the signal to be recovered, fast acquisition time for phase locking , wide tracking range, and wide frequency tunability.

We thank M. Calhoun of JPL and S. Cao of E-Tek Dynamics for lending us E/O modulators used in the experiments. This research is carried out by the Jet Propulsion Laboratory under a contract with the National Aeronautics and Space Administration.

REFERENCES

[1] R. D. Esman, K. J. Williams, M. H. White, and V. Uzunoglu, *"Microwave subcarrier and clock recovery by an optically injected CPSO,"* IEEE Photon. Techn. Lett. 3 (2), pp 179–181 (1991).

[2] K. Smith and J. K. Lucek, *"All-optical clock recovery using a mode-locked laser,"* Electron. Lett., 28(19), pp 1814–1816, 1992.

[3] A. D. Ellis, K. Smith, and D. M. Patrick, *"All optical clock recovery at bit rates up to 40 Gb/s,"* Electron. Lett., 29(15), pp 1323–1324 (1993)

[4] D. M. Patrick and R. J. Manning, *"20 Gb/s all-optical clock recovery using semiconductor nonlinearity,"* Electron. Lett., 30(2), pp 151–152 (1994)

[5] P. E. Barnsley, H. J. Wicks, G. E. Wickens, and D. M. Spivit, *"All- optical clock recovery from 5 Gb/s RZ data using a self-pulsating 1.56 m laser diode,"* IEEE Photon. Techn. Lett. 3(10), pp 942–945 (1991)

[6] M. Jinno and T. Matsumoto, *"All-optical timing extraction using a 1.5 m self-pulsating multielectrode DFB LD,"* Electronic Letters 24(23), pp 1426– 1427 (1988)

[7] X. S. Yao and L. Maleki, *"High frequency optical subcarrier generator,"* Electron. Lett., 30(18), pp. 1525–1526 (1994).

[8] X. S. Yao and L. Maleki, *"Light Induced Microwave Oscillator,"* Submitted to Journal of Optical Society of America B. Also in The TDA Progress Report 42–123, Jet Propulsion Laboratory, http://tda.jpl.nasa.gov/progress_report, pp. 32–42 (1995).

[9] X. Steve Yao and Lute Maleki, *"A novel photonic oscillator,"* The TDA Progress Report 42–121, Jet Propulsion Laboratory, pp. 32–42 (1995), http://tda.jpl.nasa.gov/progress_report.

[10] D. Wolever, Phase-locked circuit design, Prentice Hall, Englewood Cliffs, 1991.

[11] H. Ichino, M. Tugasshi, M. Ohhata, Y. Imai, N. Ishihata, G. Sano, *"Over-10-Gb/s ICs for future light wave communications,"* J. Lightwave Techn., 12(2) pp 308–319 (1994).

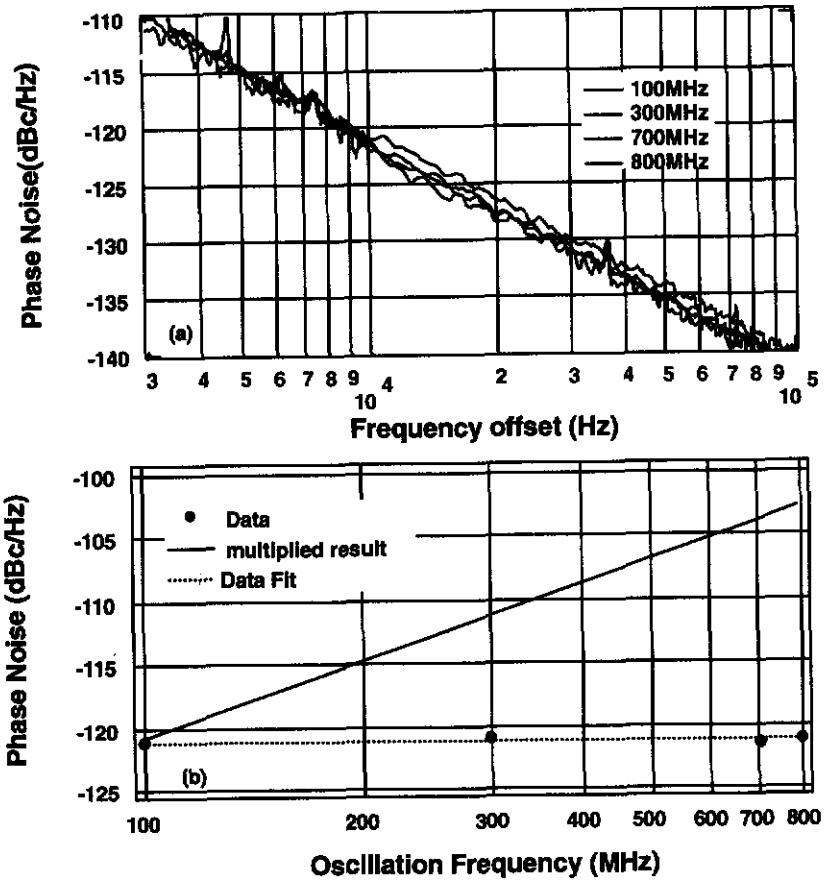


Fig. 3. The phase noise of the LIMO at different frequencies.

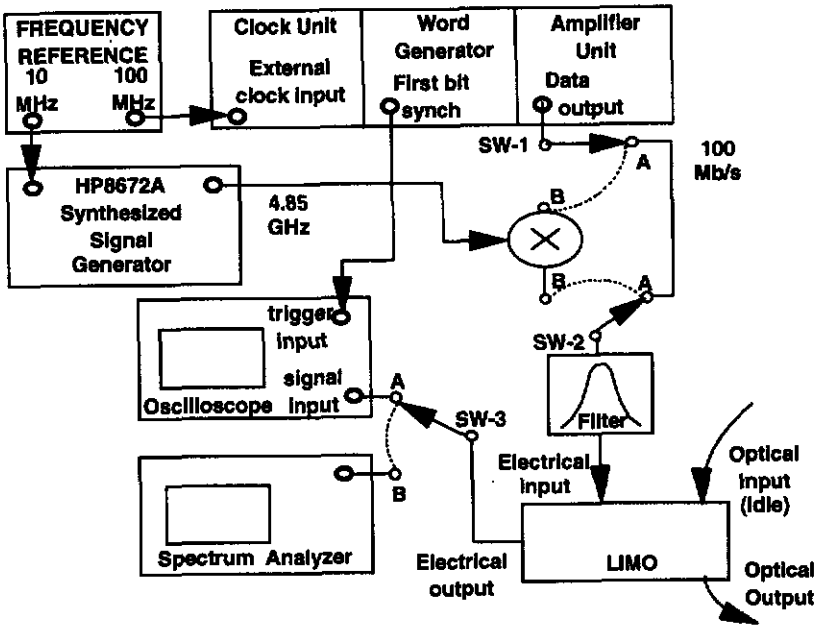
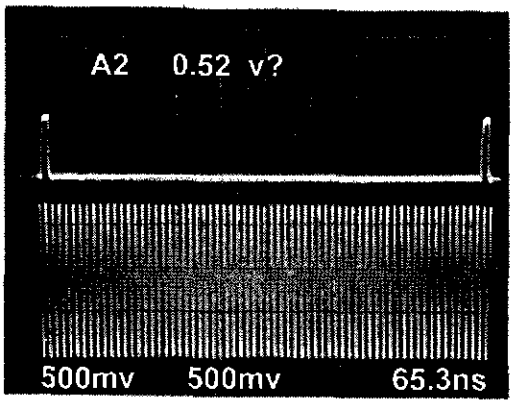
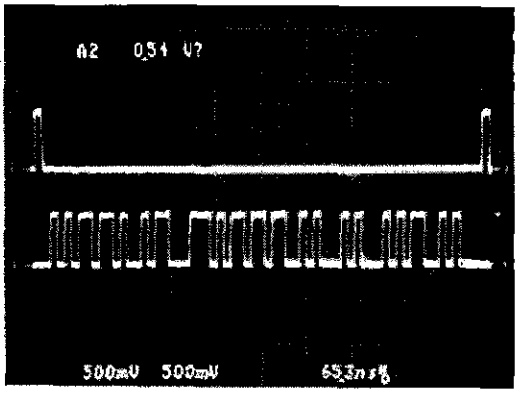


Fig. 4 The experimental setup used to demonstrate 100 MHz and 4.95 GHz clock.

(a)



(b)



(c)

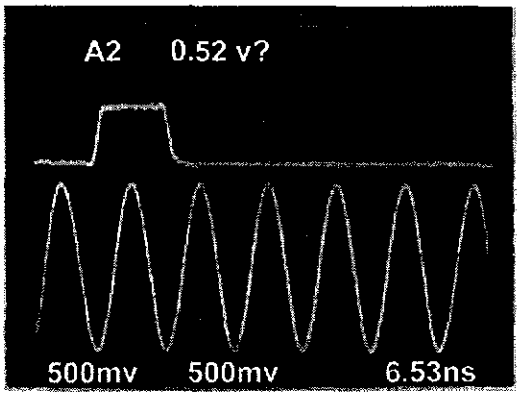
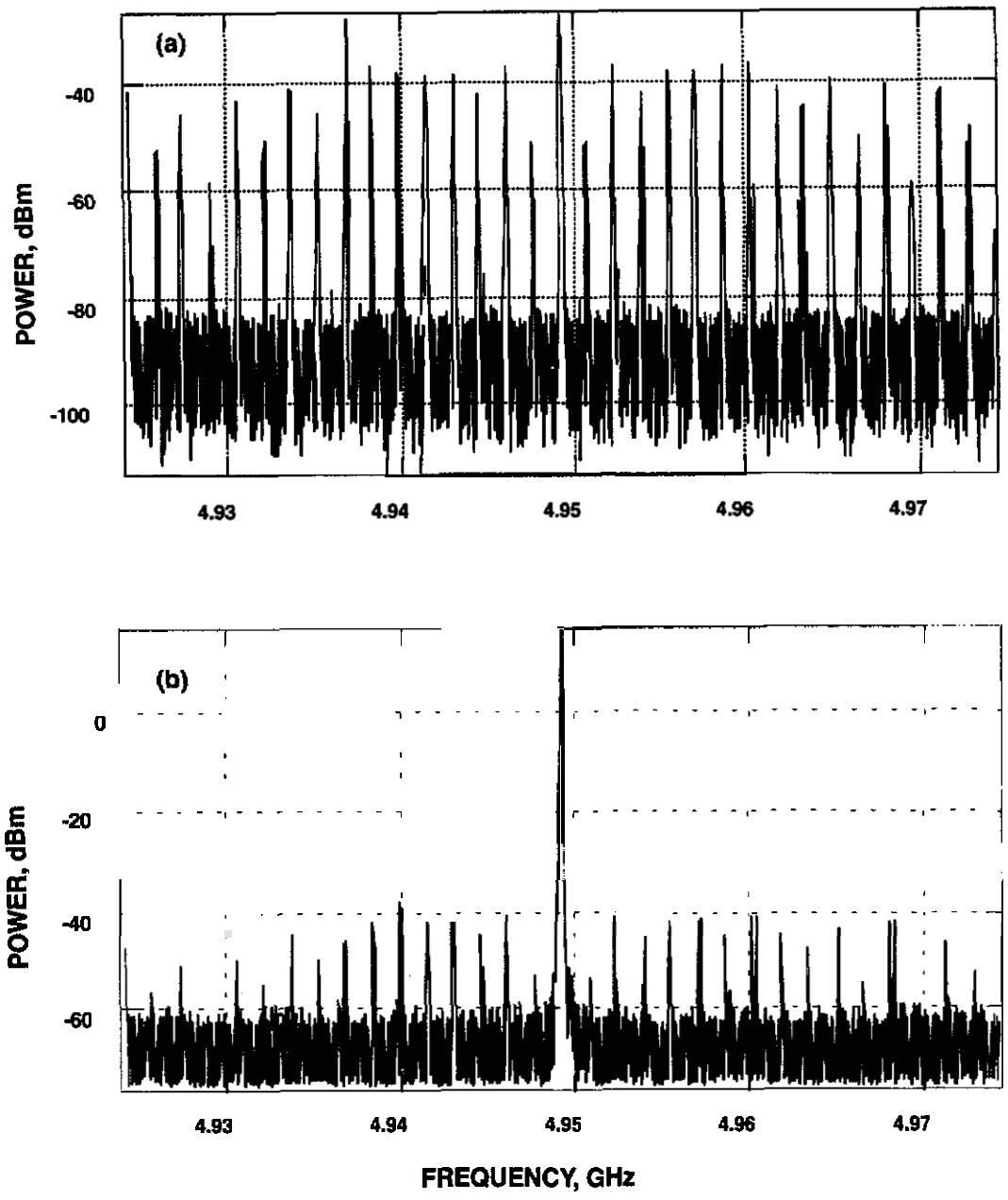


Fig. 5 The oscilloscope display of the experimental results in the tme domain. (a) shows the input data, while (b) and (c) show the recovered clock. In (c) the time span was reduced 10 times to show the recovered clock in more detail. In all three figures, the upper trace is the first bit of the input data used to trigger the oscilloscope.



Figs. 6(a) and 6(b) show the frequency spectrum of the data before and after clock recovery.

Questions and Answers

DAVID ALLAN (ALLAN'S TIME): What kind of powers have you been able to appreciate at this point? I know you have to have the amplifier in a loop.

GEORGE LUTES (CALIFORNIA INSTITUTE OF TECHNOLOGY): You mean the total DC input powers?

DAVID ALLAN (ALLAN'S TIME): Yes.

GEORGE LUTES (CALIFORNIA INSTITUTE OF TECHNOLOGY): Well, the way we're running, it's fairly high. However, lasers, sonic electro-lasers, have been becoming very efficient. Lasers better than 50 percent efficiency and are becoming available. So it's hard to tell exactly how low we can get the power. But, I suspect that in the future, if we find some good applications for this device, that we'll be able to put it on a single chip, an optical chip – except for the fiber, the delay line, of course. I think that power can be gotten down to certainly less than a watt.

Then there's another aspect to this oscillator, too, that might be interesting to some people. We believe that it will not be nearly as susceptible to vibration as other types of oscillators that use tuning devices, such as crystals and saw delay lines and things like that which are very susceptible to microphonics. This one should be much less susceptible to that.

DAVID ALLAN (ALLAN'S TIME): Is the temperature delay of the delay line, the temperature fix on the delay line any problem at all?

GEORGE LUTES (CALIFORNIA INSTITUTE OF TECHNOLOGY): Well, it is. If you want really high stability, we have done some calculations using a low thermal coefficient of delay fiber for the delay line. And it has a very broad curve that goes through a zero coefficient of delay at a certain temperature. So, we have looked at how good we think we could do if we control the temperature of the delay line to that temperature within reasonable limits.

The numbers we get are pretty amazing, but we've been in this business long enough to know that it's easier said than done! So, I'm not going to say anything about what those numbers turned out to be, but certainly better than crystal oscillators.